top physics beyond the LHC

Marcel Vos (IFIC, CSIC/UV, Valencia, Spain)

Perspectives/Future Colliders, Top 2016,

Olomouc (CZ), 23 September 2016

Top physics prehistory

1973: The top quark is born as a hypothetical particle

Kobayashi and Maskawa postulate the third generation

Particle physics was so easy then!

1972 A 5M$ collider starts operation on the SLAC parking lot

1974 Two colliders in the same country discover the same particle

Top physics in 1995

1995: Experimental confirmation, the birth of the top quark

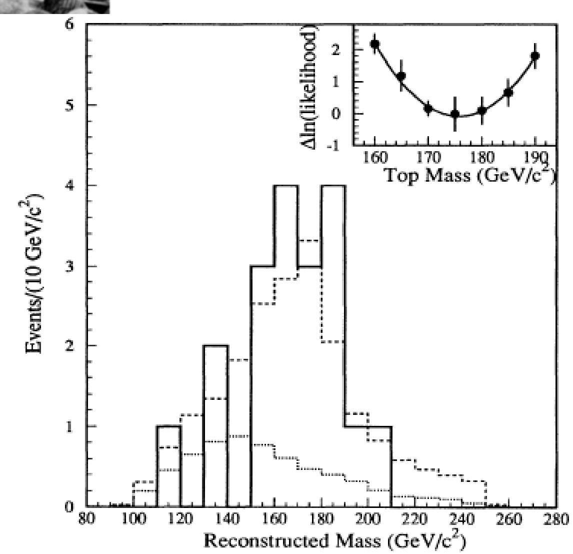
Virtual (LEP/SLC): Top quark implies radiative corrections to relation of G_F, α, θ_w, m_Z

e^+e^- precision data ultimately predicts:

$$m_t = 173\,^{+12}_{-13}\,^{+18}_{-20}$$

Real (Tevatron):
Expectation was mounting at the most powerful collider in the world.
And indeed...

CDF and D0 collaborations, Observation of the top quark
PRL 75 (1995) 2632-2637, 2626-2631



Pick your project: HERA/LEP/SLC/Tevatron

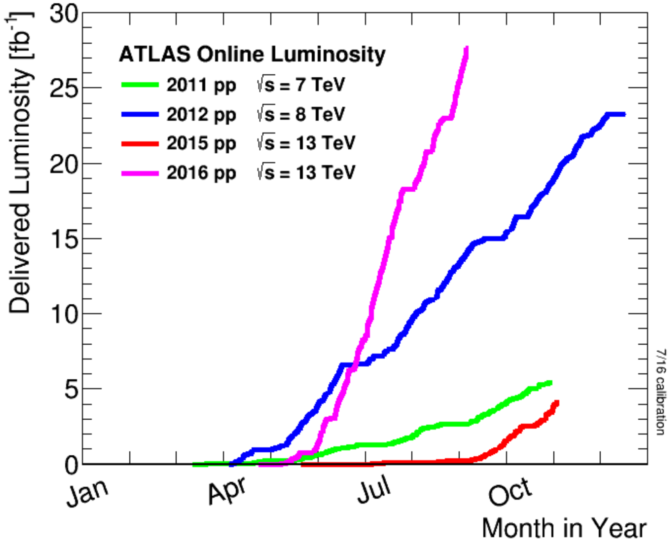
Thank God for the LHC

(Differential) cross section measurements

- in $p\bar{p}$ and pp and at multiple energies (2, 5, 7, 8, 13 TeV)

Charge asymmetry, top decay, spin correlations

Associated production with EW gauge bosons

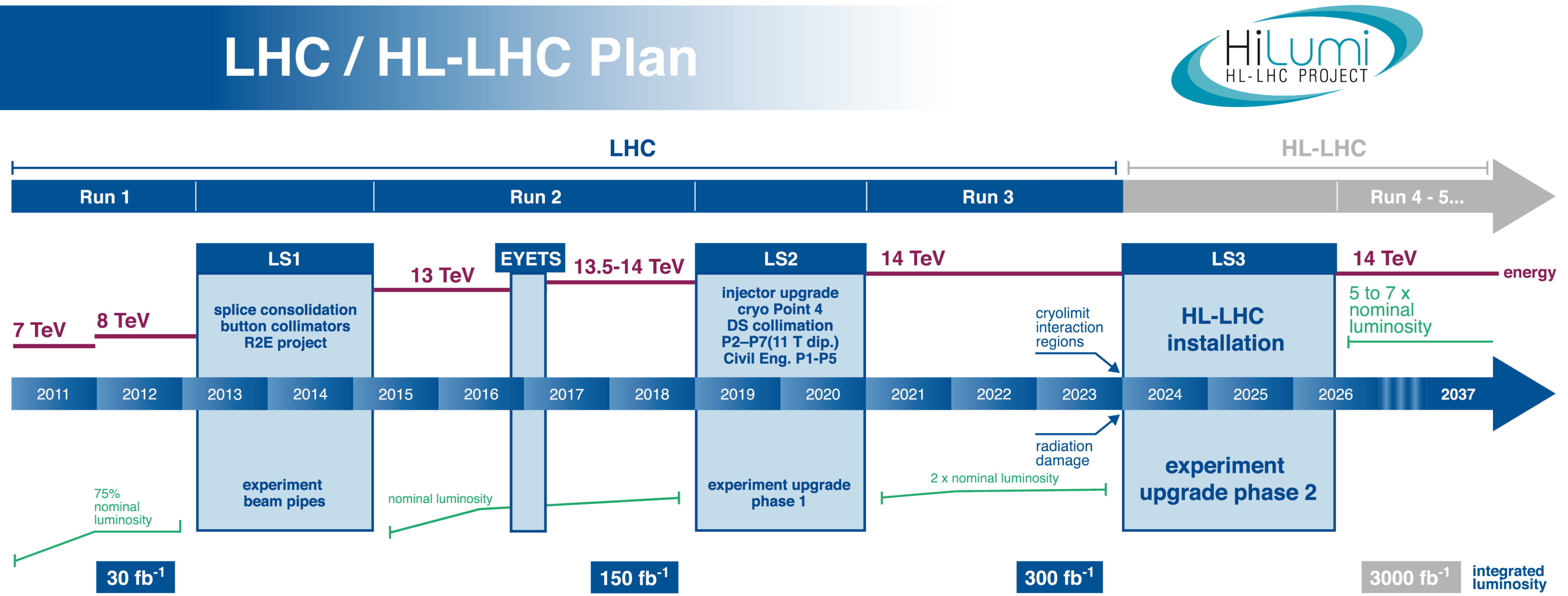


Fortunately, we've got LHC for a while

The full exploitation of the LHC is the highest priority in the European Strategy for Particle Physics, adopted by the CERN Council and integrated into the ESFRI Roadmap.

The HL-LHC project funding was approved by the CERN Council in June 2014.

Top physics potential covered in Patrizia Azzi's talk.



What's next?

Can/should we build another big collider?

Discovery/Installation/laboratory	**Year**
Muon discovered (cosmic rays)	1936
Kaon (cosmic rays)	1942
Muon neutrino, AGS, BNL	1962
Quarks, DIS, SLAC	1968
Neutral current, PS, CERN	1974
J/psi, AGS, BNL/SPEAR, SLAC	1974
τ-lepton, SPEAR, SLAC	1977
Upsilon, bottom quark, PC, FNAL	1977
Gluon, Petra, DESY	1979
W and Z, SPPS, CERN	1983
top quark, Tevatron, FNAL	1995
Higgs boson, LHC phase I, CERN	2012

History is on our side!

Yes, we should!
And, yes, we can too!

Steve Weinberg, The Crisis of Big Science

There are things that can be done in fundamental physics without building a new generation of accelerators. We will go on looking for rare processes, like an extremely slow conjectured radioactive decay of protons. There is much to do in studying the properties of neutrinos. We get some useful information from astronomers. **But I do not believe that we can make significant progress without also pushing back the frontier of high energy.**

What do we need to build the next collider(s)?

(1) **Funding**, well beyond regular budget

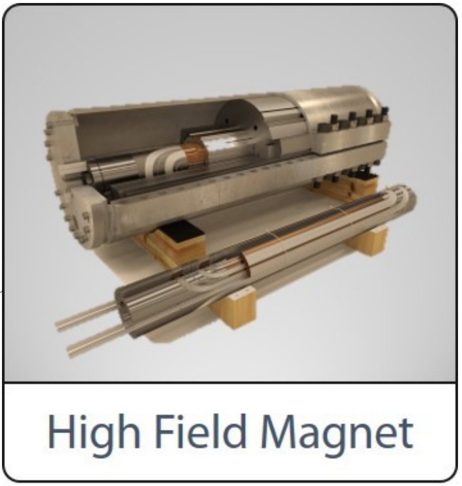
The next project is going to be truly global
Coordinate globally to maximize scientific return

Europe → LHC + FCC

US → neutrino physics

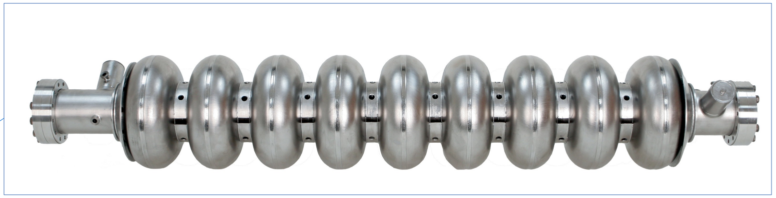
Can Asia step forward?
ILC/CEPC/SPPC

(2) **Technology** to achieve a big leap in center-of-mass energy



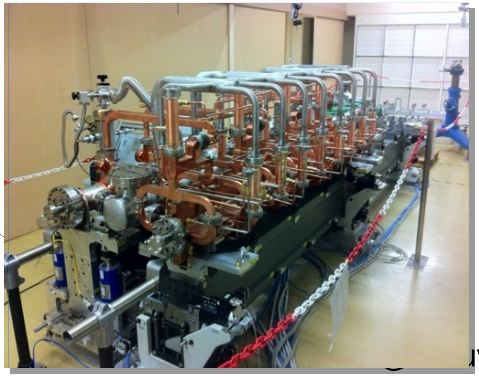
Bending magnets

→ 4 Tesla (Tevatron)
→ 8 Tesla (LHC)
→ 16 Tesla (VLHC, SPPC, FCChh)
Key R&D programme in EU strategy



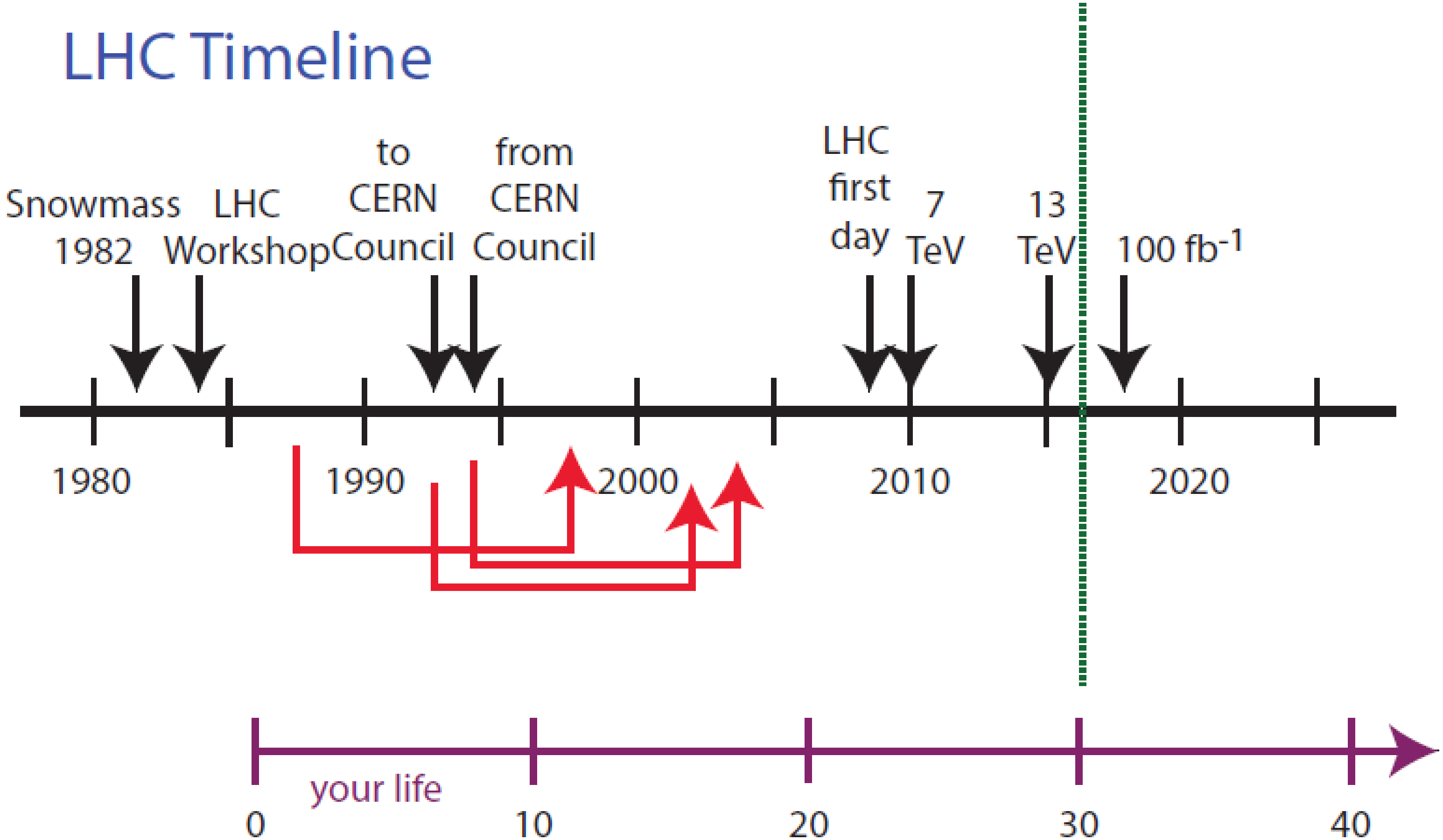
Accelerating cavities

→ 17 MV/m cavities (SLC)
→ 35 MV/m (industry, XFEL/ILC)
→ 100 MV/m (concept proven, CLIC)
→ Plasma wakefield (when?)



What do we need to build the next collider

(3) Time



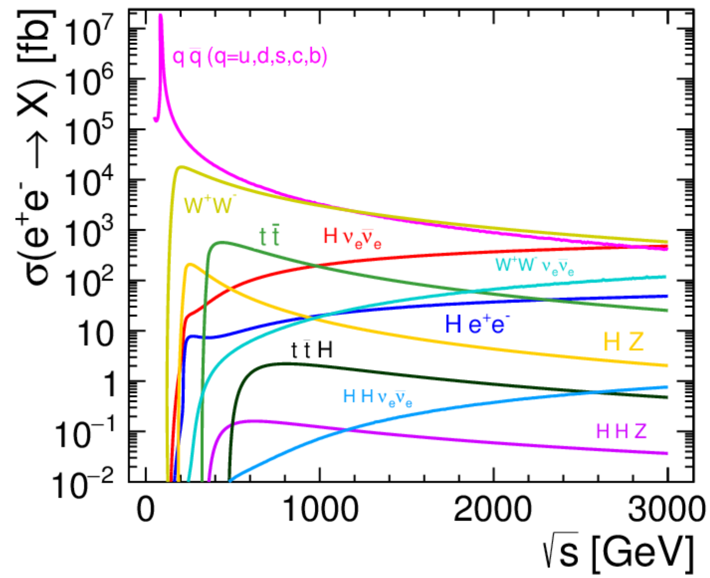
From: Michael Peskin, SEARCH 2016

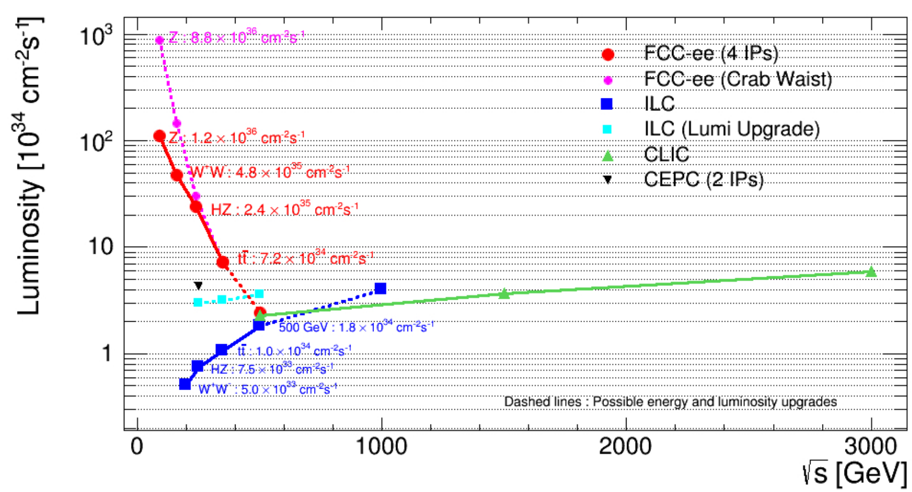
Top physics at a lepton collider?

Lepton collider projects:

- ILC (TDR, negotiations):
  250, 500, 1000 GeV
- CLIC (CDR):
  380, 1500, 3000 GeV
- CEPC (pre-CDR, TDR ~2020):
  250 GeV → no $t\bar{t}$ production
- FCC-ee (exploration):
  365 GeV

Technology exists today
Detailed designs for ILC/CLIC



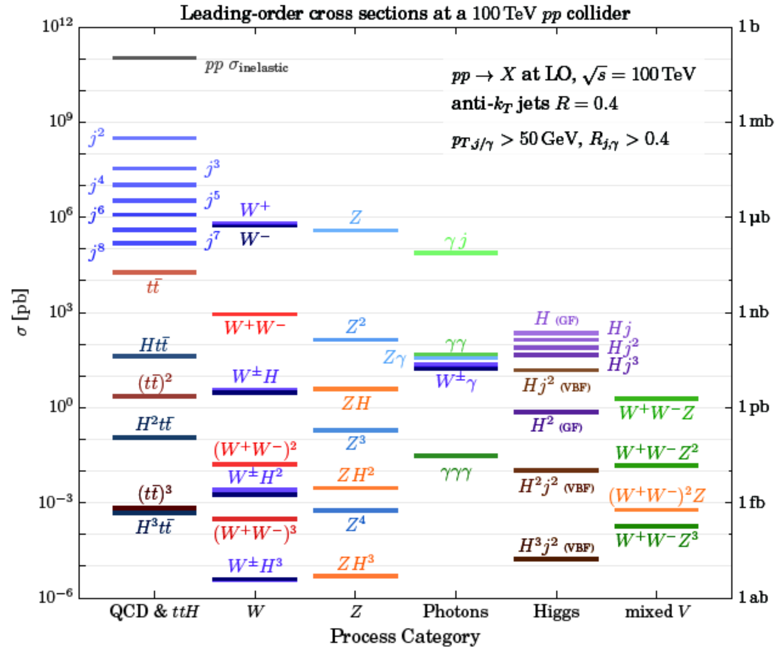


Top physics at the next hadron collider?

Projects for the next very large hadron collider

16 Tesla Nb3Sn magnet R&D to allow √s/L ~1 TeV/km

- **SPPC (China, conceptual design end 2016)**
  50-80 km (TeV)
- **FCChh (CERN, CDR ~2018)**
  Up to 100 km (TeV)
- **High-E LHC**
  LEP/LHC tunnel 27 km (or TeV)



ArXiv:1605.00617

(4) **Faith** that the next machine can deliver a profound transformation of particle physics

The "LHC no-loose theorem"; no such thing exists for the next machine (yet)
Can we prove BSM physics is hiding around the next corner?
X(750) reminds us that a discovery can tilt the playing field overnight

Meanwhile, Standard Model physics - and agnosticly defined BSM sensitivity - is an important benchmark

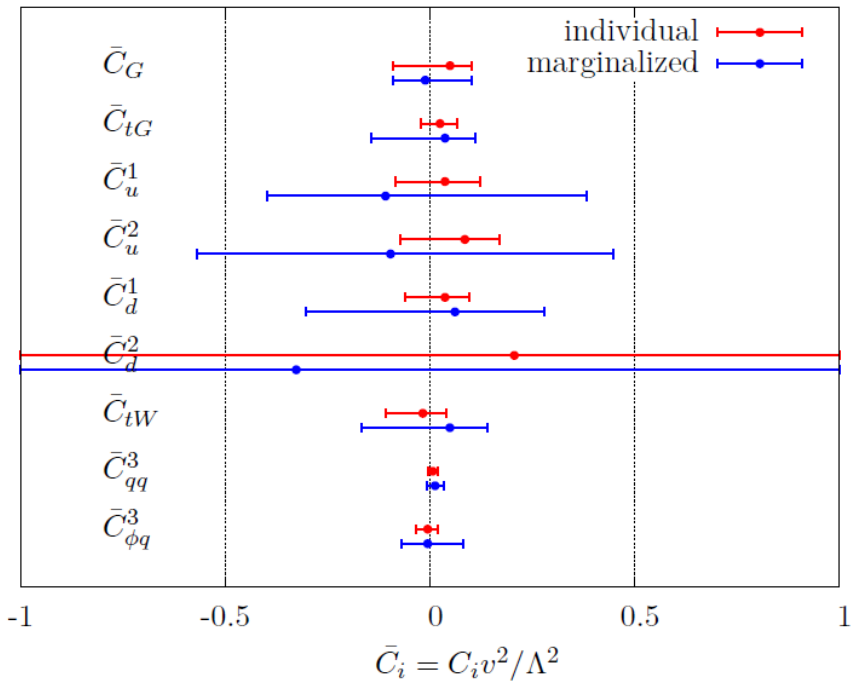
How can we even start to evaluate the (top physics) potential of projects with fundamentally different approaches?

A framework to compare projects?

Simultaneous fit to ~ all data
arXiv:1506.08845, arXiv:1512.03360

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

EFT analyses to quantify the potential and study the complementarity of different programs...



I'll be presenting a mixture of bounds on form factors and D6 operators (with formulae relating the two wherever I had them available)

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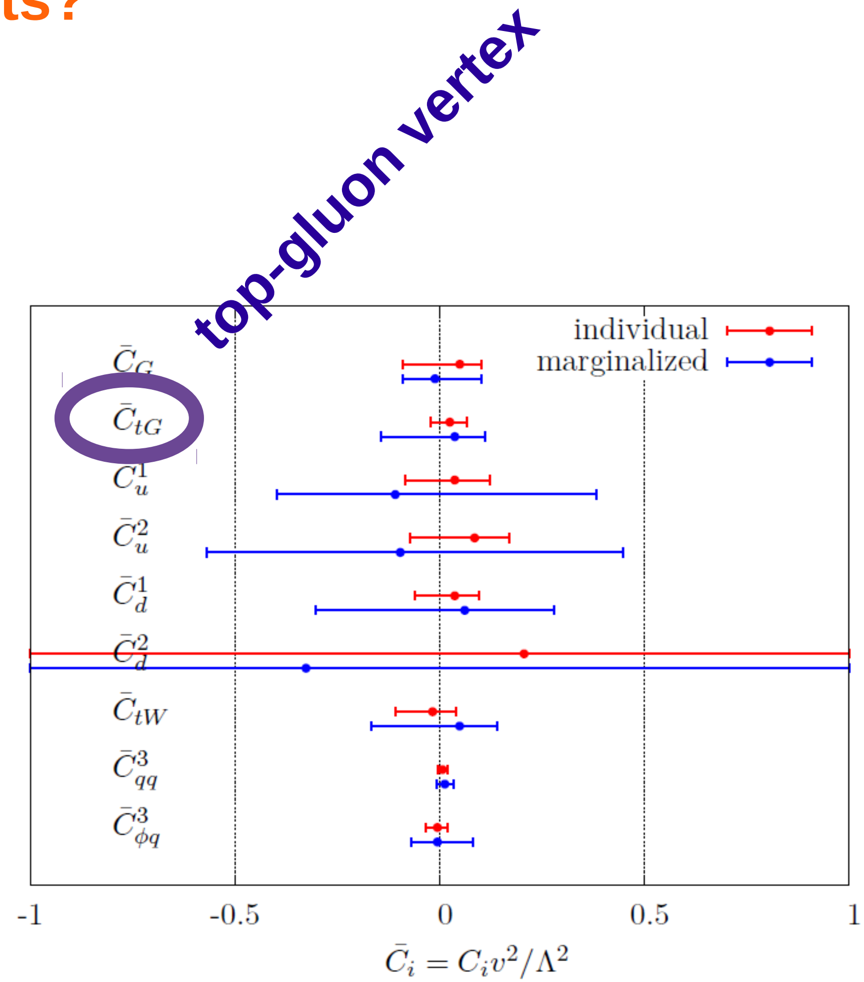

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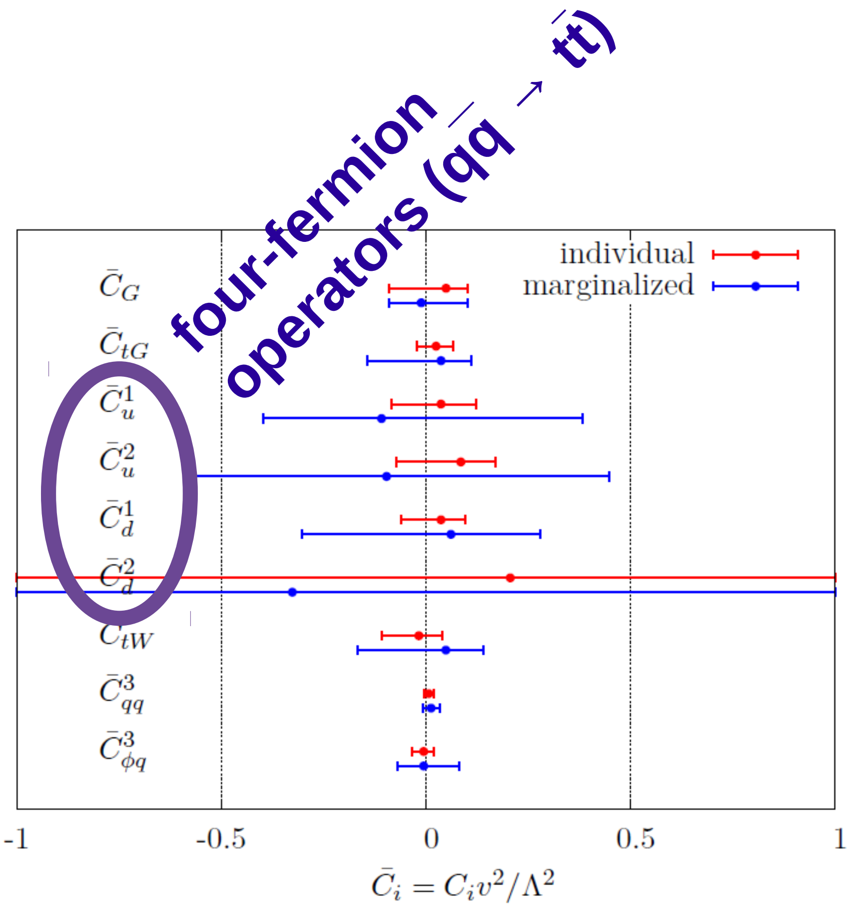

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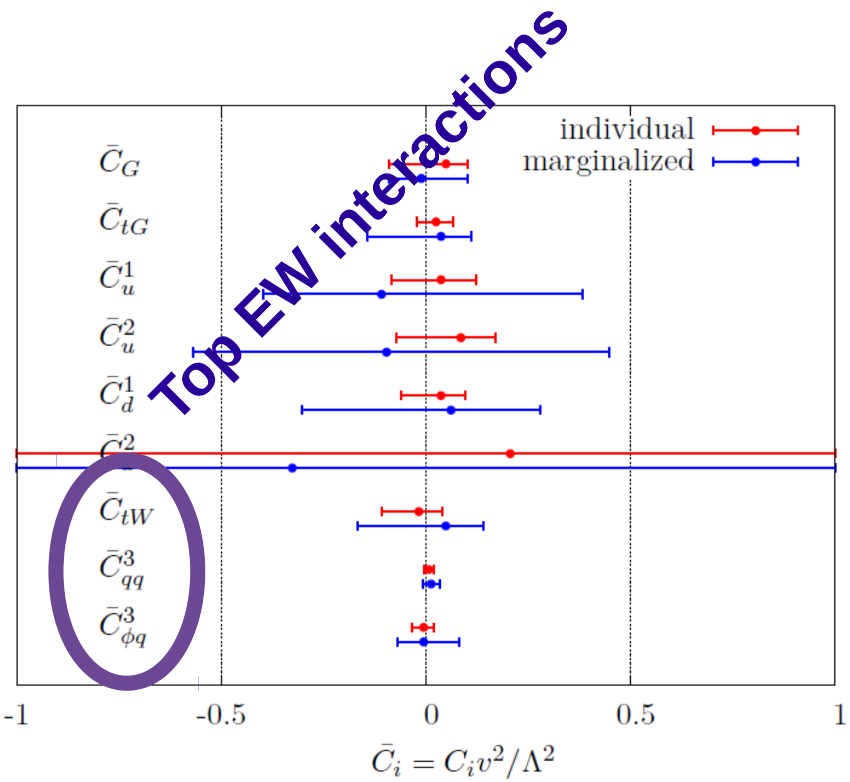

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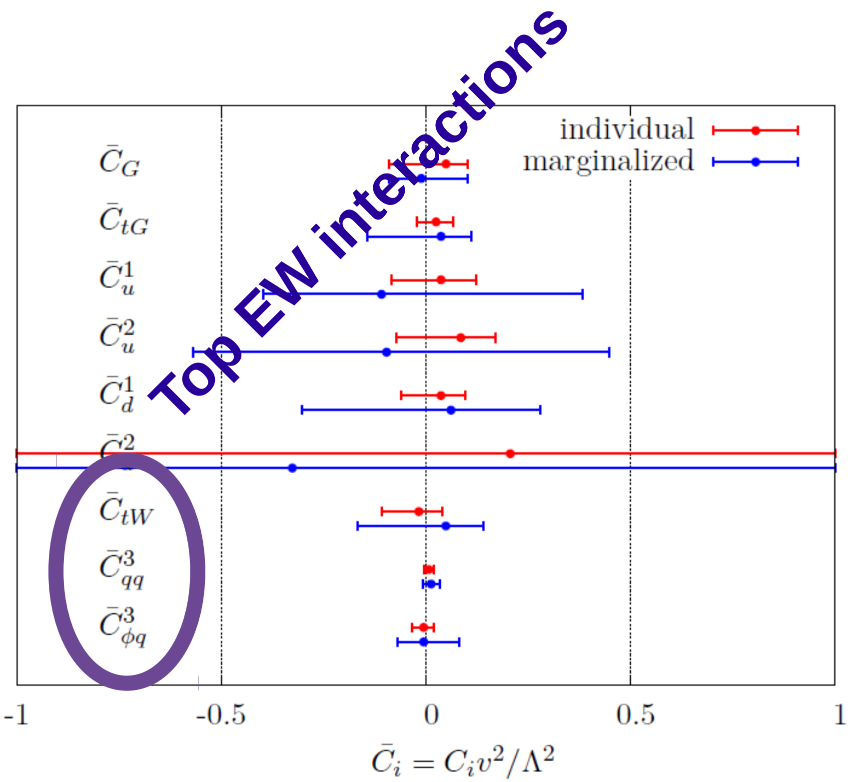
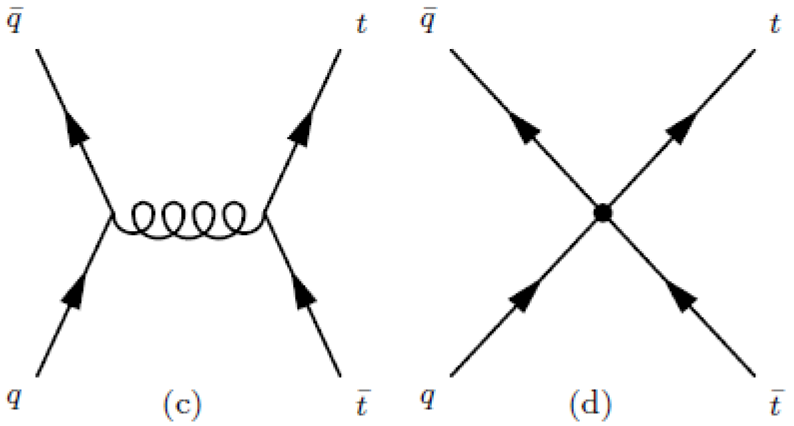
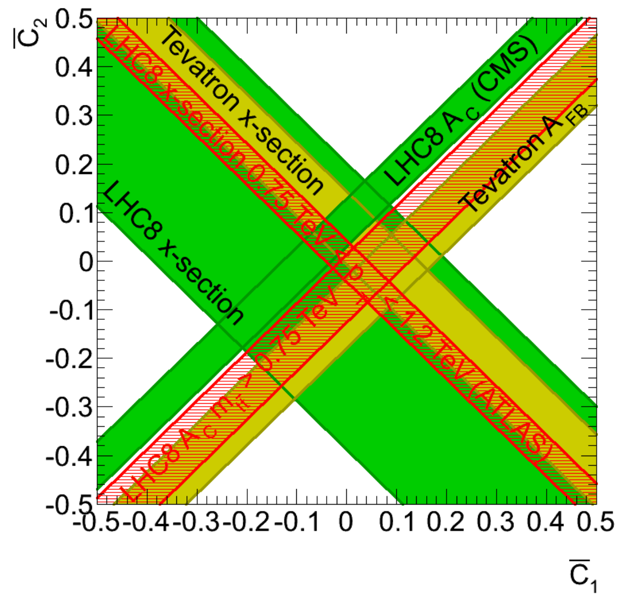


Machinery for automated NLO treatment appearing (see Durieux, Vryonidou, this workshop)

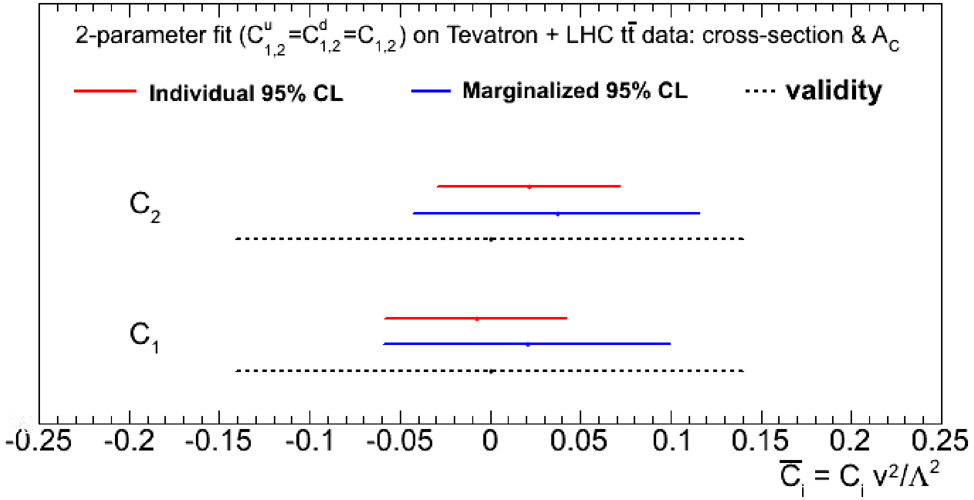
I'll be presenting a mixture of bounds on form factors and D6 operators (with formulae relating the two wherever I had them available)

Example: comparison of the Tevatron-LHC potential to constrain four-fermion operators





Heavy gluon exchange represented by dimension-6 four-fermion operators



Cross-section and A_C provide complementary constraints

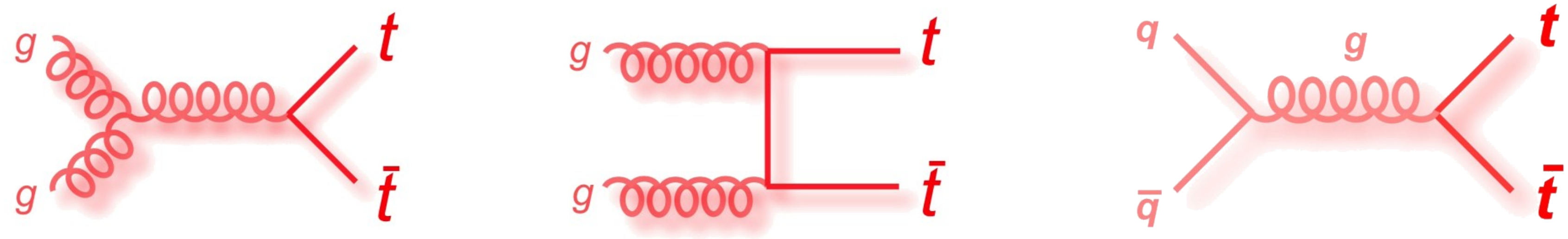
LHC vs. Tevatron: use higher boost to produce tight constraints

M. Perelló, M. Vos, arXiv:1512.07542

Top quark production
Hadron and lepton colliders
Precision physics

Top quark production at hadron colliders

Hadron colliders are top quark factories



# tt events	*Tevatron run II* 10 fb^{-1} @ 1.96 TeV	*LHC 2012* 20 fb^{-1} @ 8 TeV	LHC sep-2016 30 fb^{-1} @ 13 TeV	*LHC design* 300 fb^{-1} @ 13 TeV	*HL-LHC* 3 ab^{-1} @ 13/14 TeV
tt production	57 k	2.6 M	15.5 M	155 M	1.55 G
M_{tt} > 1 TeV	25	30 k	300 k	3 M	30 M
M_{tt} > 2 TeV	0	300	4.7 k	47 k	470 k

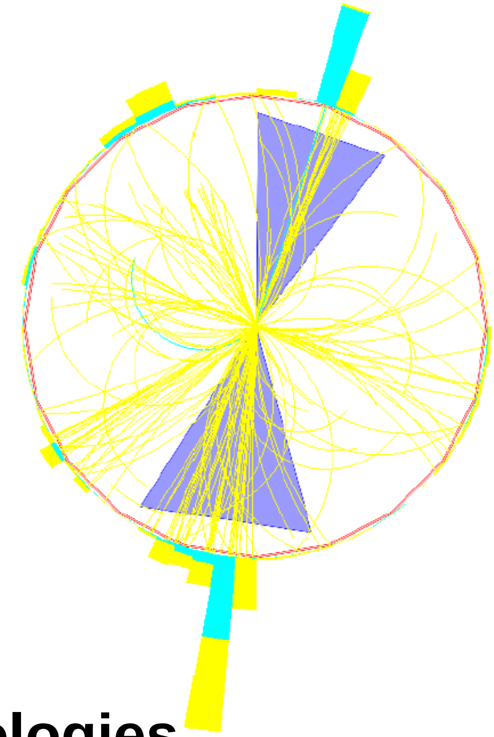
The increase in the high-energy tail is even more pronounced (analyses of boosted pair production are on their way to become bread-and-butter physics)

FCChh and SPPC are off the chart!

10 ab^{-1} at 100 TeV yields 10^{12} top quark pairs

Access to remote corners of phase space and rare processes with negligible stat. uncertainty

80-100 TeV pp collisions



Consequences of “top as a light quark”

- Production much more forward
  LHCb → FCCtop or SPPCtop...
  M. Mangano, TOP2015
- Must treat production differently:
  gluon → $t\bar{t}$ splitting, top quark PDF,
  J. Rojo/NNPDF, arXiv:1607.01831

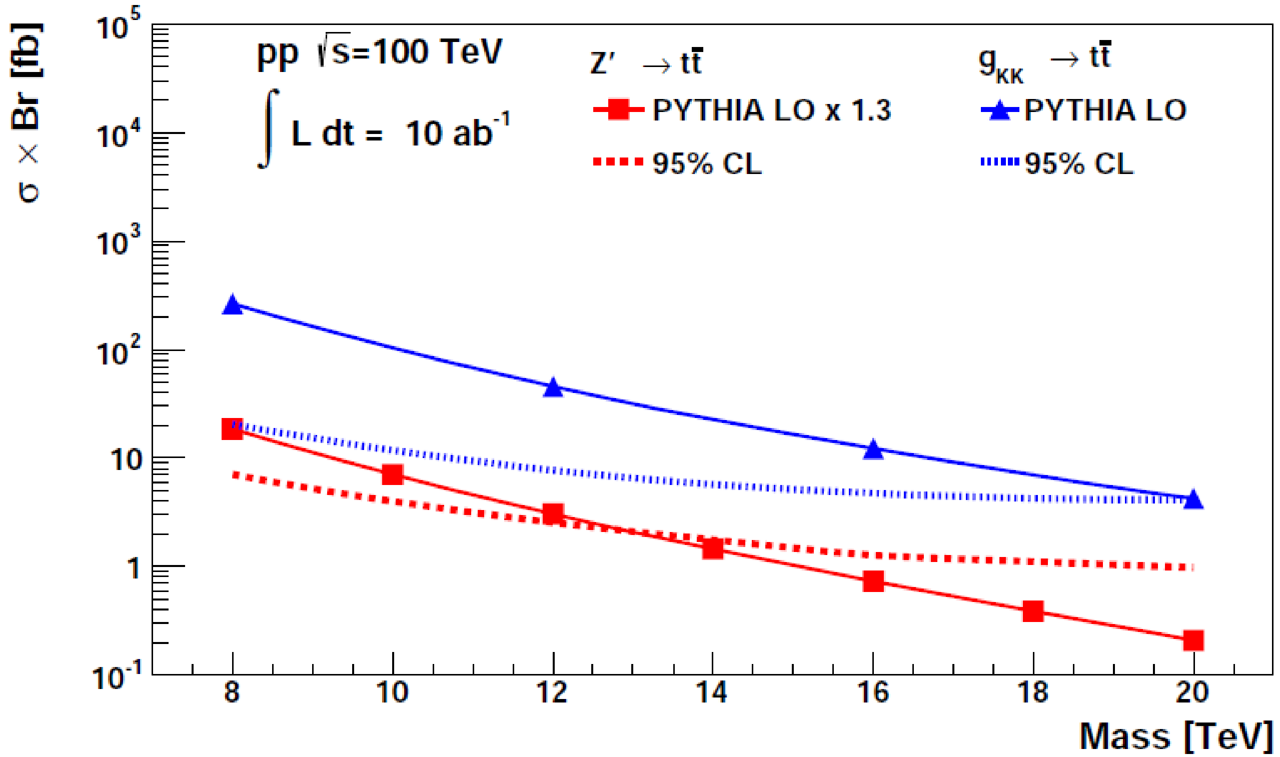
Must deal with ultra-boosted decay topologies

Ambition

- Lepton requirement may be sufficient in some case
  Saavedra et al. arXiv:1412.6654
- Charged substructure is probably adequate (if definitely not brilliant)
  A. Larkoski, arXiv:1511.06495
- Keep “good old” jet substructure and push detector granularity to new level
  $t\bar{t}$ resonance section of arXiv:1606.00947
  (Argonne study with DELPHES, arXiv:1412.5951)

Top quarks at high $t\bar{t}$ mass

Mass reach (now 2.5-3 TeV) indeed nearly scales with center-of-mass energy



Expect similar improvement in searches for W' → tb, top partners, etc.
FCChh BSM summary: *arXiv:1606.00947*

A daunting challenge, but no doubt, we'll manage!

State-of-the-art $t\bar{t}$ cross-section comparison at LHC

Exp. uncertainty on inclusive pair production cross-section: ~4%
Statistical component negligible
Systematics dominated by hadronization (even for fiducial x-sec)

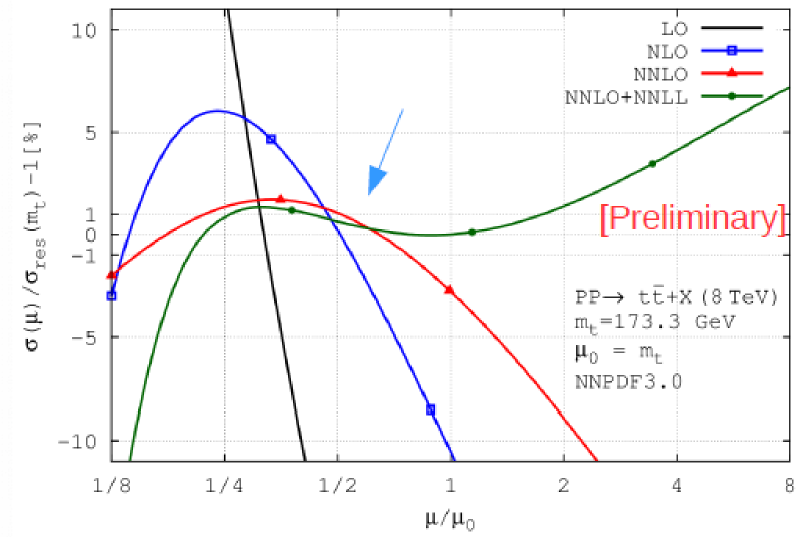
Accurate knowledge of the machine
Luminosity typically 3%
Center-of-mass energy!

Accurate knowledge of the proton
PDF (gluon at large x) to be improved
(using non-$t\bar{t}$ LHC data)

Fiducial prediction
Particle-level results affected by PS/had.

complete NNLO+NNLL prediction
(also fully differential, arXiv:1606.03350)
Scale variations reduced to few %
NNNLO in foreseeable future?

(David Heymes, Moriond QCD 2016)



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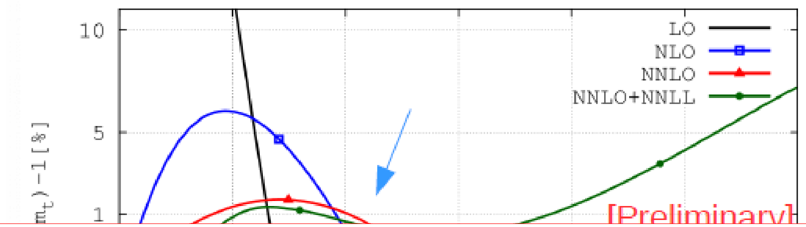


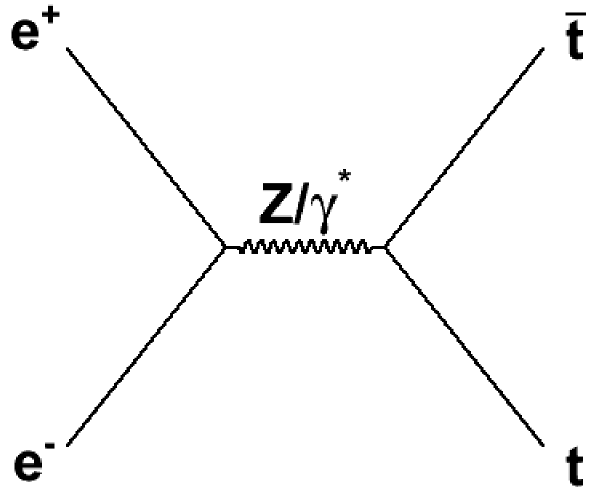
Accurate knowledge of the proton

arXiv:1507.08169: "one of the key obstacles to exploiting the immense statics available at hadron colliders for precision measurements, is the intrinsic difficulty in performing accurate absolute rate predictions"

Work-around: ratios (more later in the talk)

(also fully differential, arXiv:1606.03350)
Scale variations reduced to few %
NNNLO in foreseeable future?

Top quark production at lepton colliders



For precision there is nothing like e^+e^-

Machine: per mil level luminosity, polarization and beam energy calibration

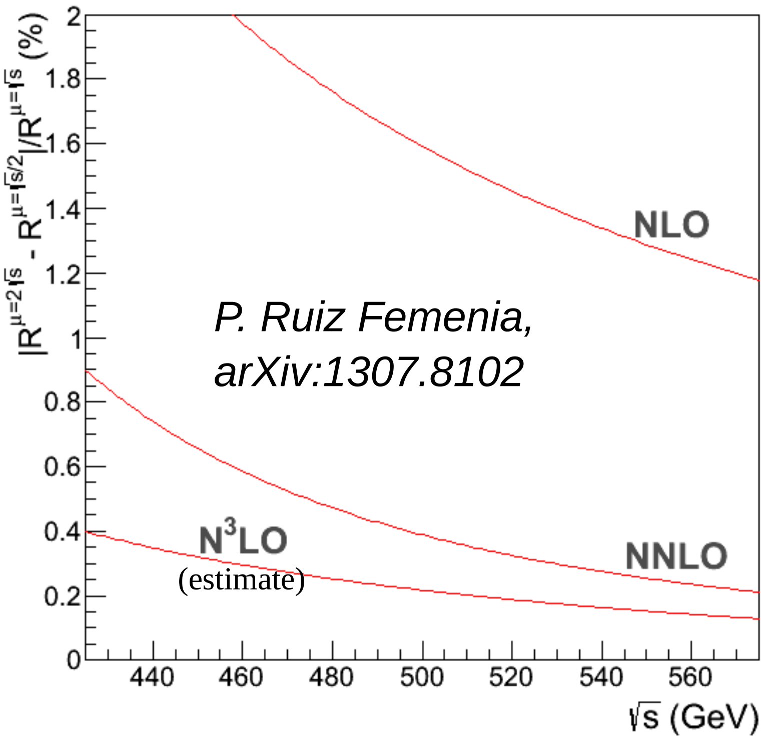
Theory: no PDFs, small QCD corrections
Predictions at few per-mil level already today!

Truly inclusive measurements!

Statistics: few 100.000 events, less at high energy

Experiment must match few per mil precision

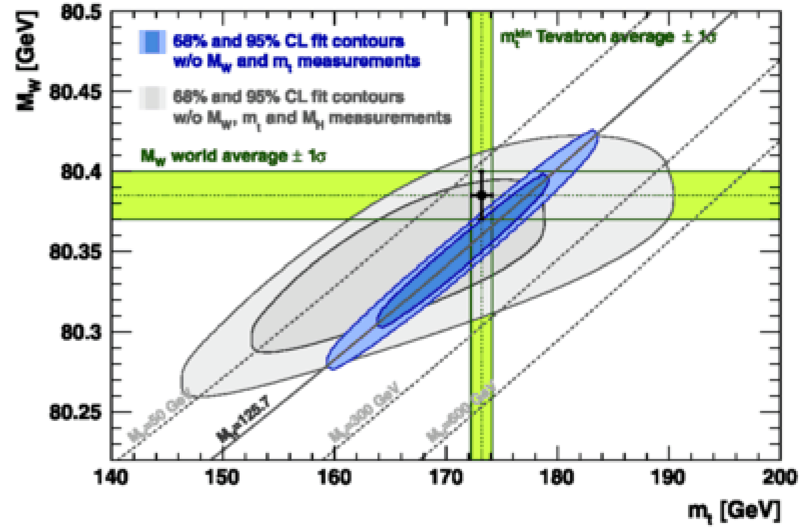
Variation in x-section due to scale variations



See also: Chokoufé et al., arXiv:1609.03390

Objetive I: top quark mass

Top quark mass



A key parameter of the SM

As m_t enters in loop corrections a precise measurement is needed to reduce parametric uncertainties

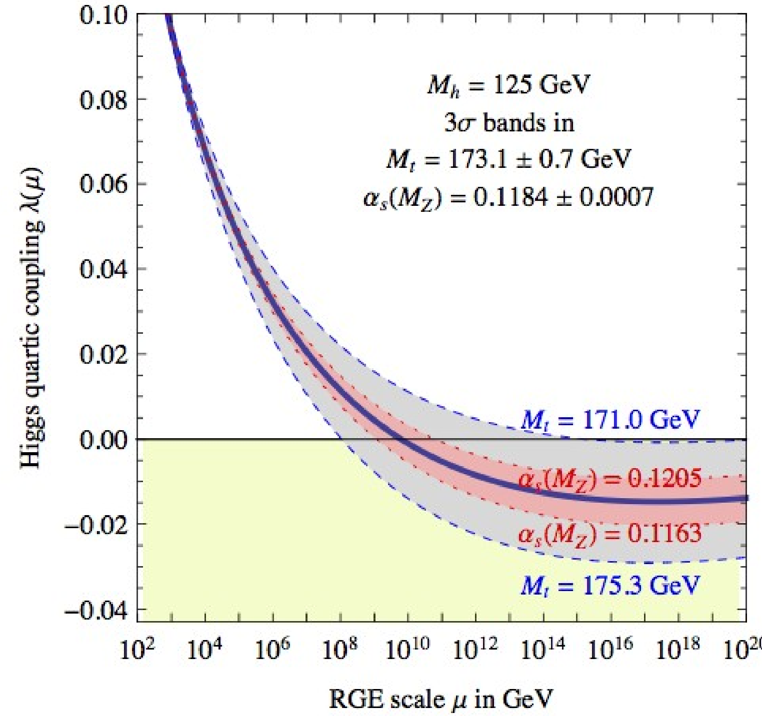
Precision test of the SM

SM relation H, W, t mass → EW fit

Currently limited by m_W, must improve α_s, $\sin^2\theta$, m_Z

Top may drive the Higgs potential negative

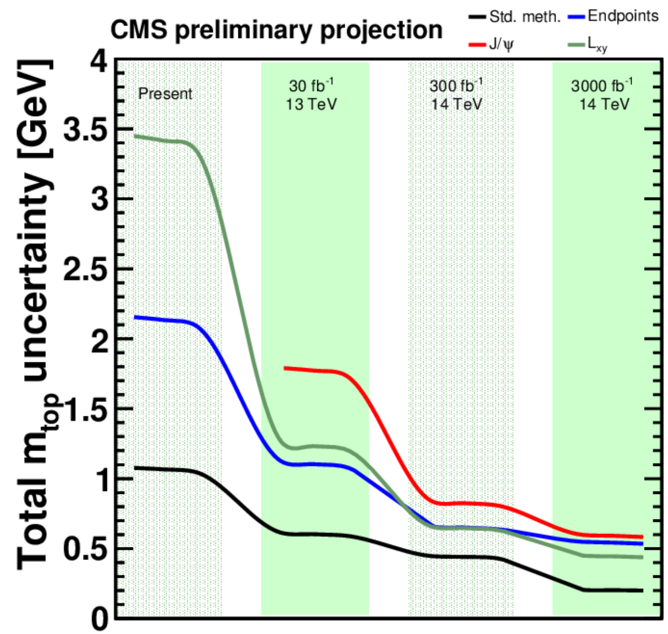
But universe not likely to decay any time soon



Top quark mass

Direct measurements yield ~500 MeV precision

Well beyond 1 GeV prospected in ATLAS TDR



Expected exp. progress

How much better can it get?

Not much. Snowmass, arXiv:1310.0799: *"a top mass extraction with uncertainty as low as 500-600 MeV [after 3/ab HL-LHC]"*

Quite a bit. *CMS-FTR-13-017-PAS: 200 MeV, "assumptions [that] are optimistic but not unrealistic [after 3/ab HL-LHC]"*

We don't know. *Mangano et al., arXiv:1607.01831: "We avoid here a discussion of the determination of the top mass at 100 TeV: any progress relative to what will be known at the end of the LHC will depend on theoretical progress that is hard to anticipate"*

Direct mass measurement is interpreted ~ pole mass

1 GeV uncertainty assigned in Tevatron/LHC combination, *arXiv:1403.4427*

Uncertainty due to hadronization estimated by varying MC models

Not a very solid basis for a 200 MeV measurement *(personal view)*

First attempt to provide a more quantitative MC mass interpretation

Non-negligible shift in e^+e^- observables, *arXiv:1608.01318*

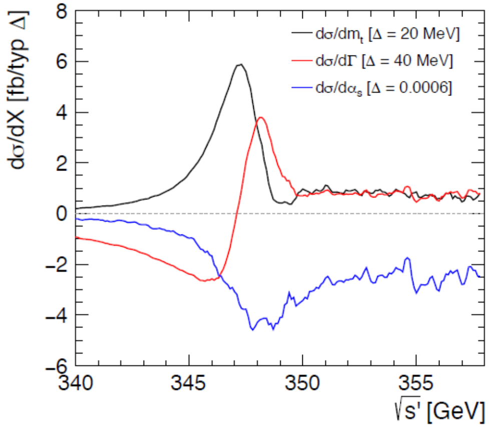
Alternative methods to reach 1 GeV soon, scope for further progress unclear

CMS-FTR-13-007-PAS, arXiv:1303.6415

Top quark mass from threshold scan

Threshold shape depends strongly on mass & width, normalization is sensitive to α_s and y_t

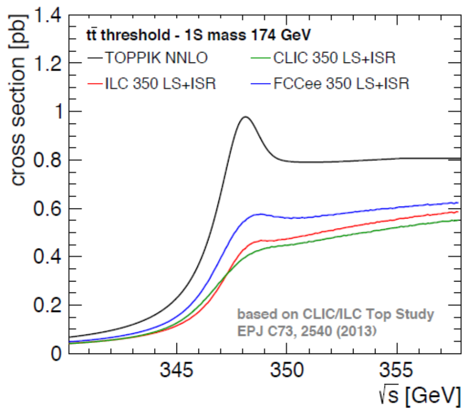
Kuhn, Acta Phys.Polon. B12 (1981)



Stat. precision 1S/PS mass: ~20 MeV

(assuming 10 x 10/fb)

Martinez, Miquel, EPJ C27, 49 (2003)
Seidel, Simon, Tesar, Poss, EPJ C73 (2013)
Horiguchi et al., arXiv:1310.0563

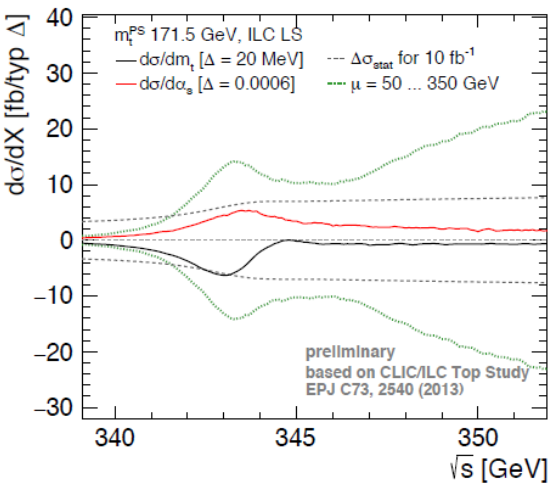


Experimental systematics: O(30 MeV)

Theory uncertainty: 50 MeV

(shape fit + 1S → $\overline{\text{MS}}$ conversion)

Beneke et al., 1506.06864 [hep-ph]
F. Simon, arXiv:1603.04764
P. Marquard et al., arXiv:1502.01030, PRL114 (2015)



arXiv:1604.08122

3 decades of top quark mass measurements...

Tevatron: discovery (1995) and first characterization

- Legacy δm_t < 1 GeV

LHC: direct measurements + alternatives

- *Experimental uncertainty to decrease to 200 MeV*
- *Calibration to pole mass to match this precision...*
- Alternative methods soon to yield ~1 GeV precision

Lepton collider with $\sqrt{s} \geq 2\, m_t$:

- *threshold scan can yield $\overline{MS}$ mass to 50 MeV precision! (including today's theory uncertainty)*

Note: beware of confusion between targets (10 MeV) and prospects (<100 MeV)
All lepton colliders do equally well, as long as they reach the threshold.

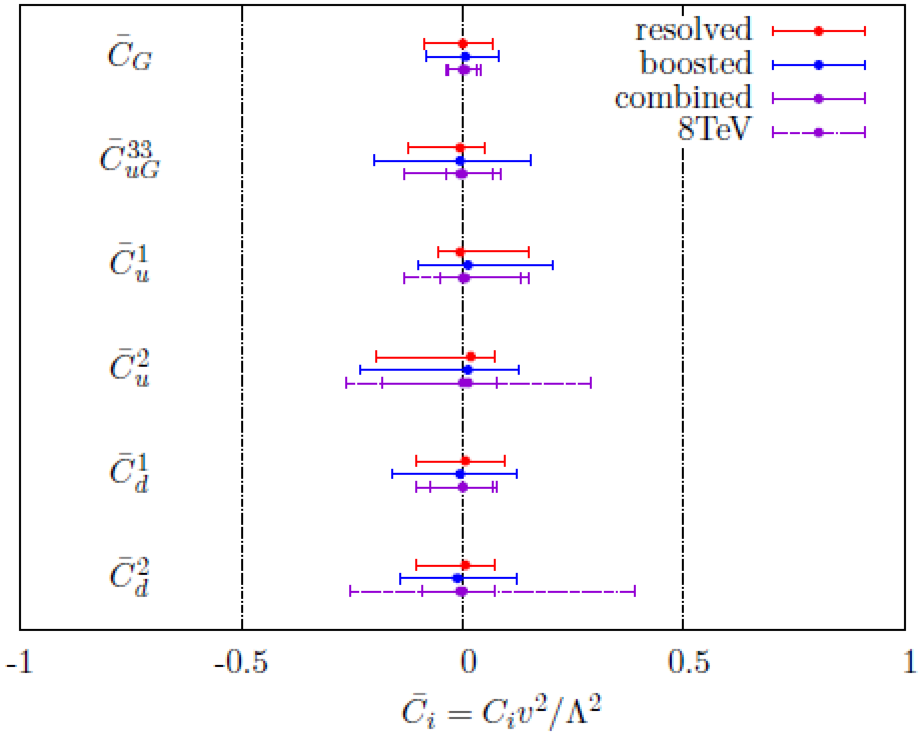
Cross section & BSM

Objetive II: rates

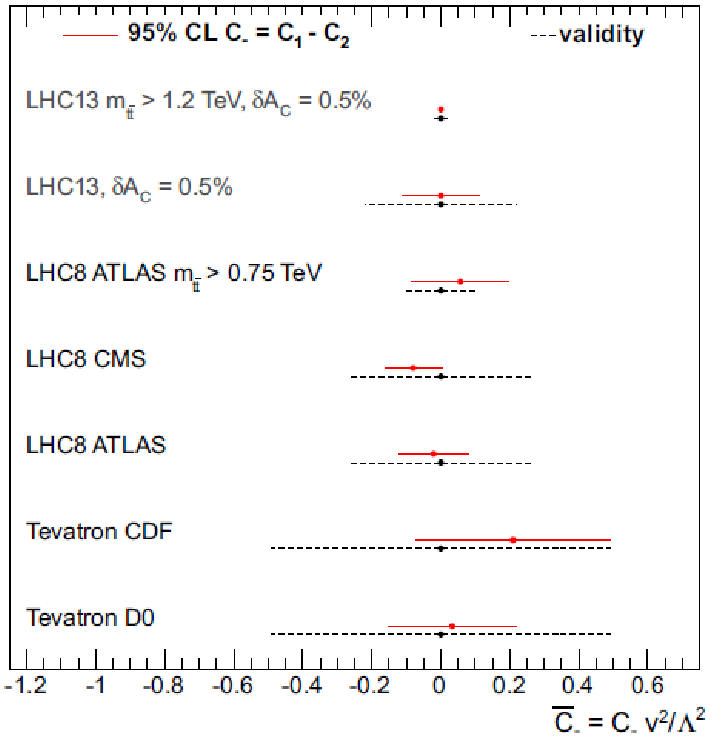
Once the top quark mass is fixed, the SM predicts production rates and properties. Precision measurements can tell whether BSM alters these.

Top and QCD

Top and QCD



Indeed, a measurement of the charge asymmetry with m(tt)>1.2 TeV and 0.5% precision shrinks the allowed region by a factor 10
arXiv:1512.07542



8 TeV fit: resolved and boosted category offer similar sensitivity
Englert et al., arXiv:1607.04304

Inclusive measurement syst-limited
Boosted expected to improve quicker

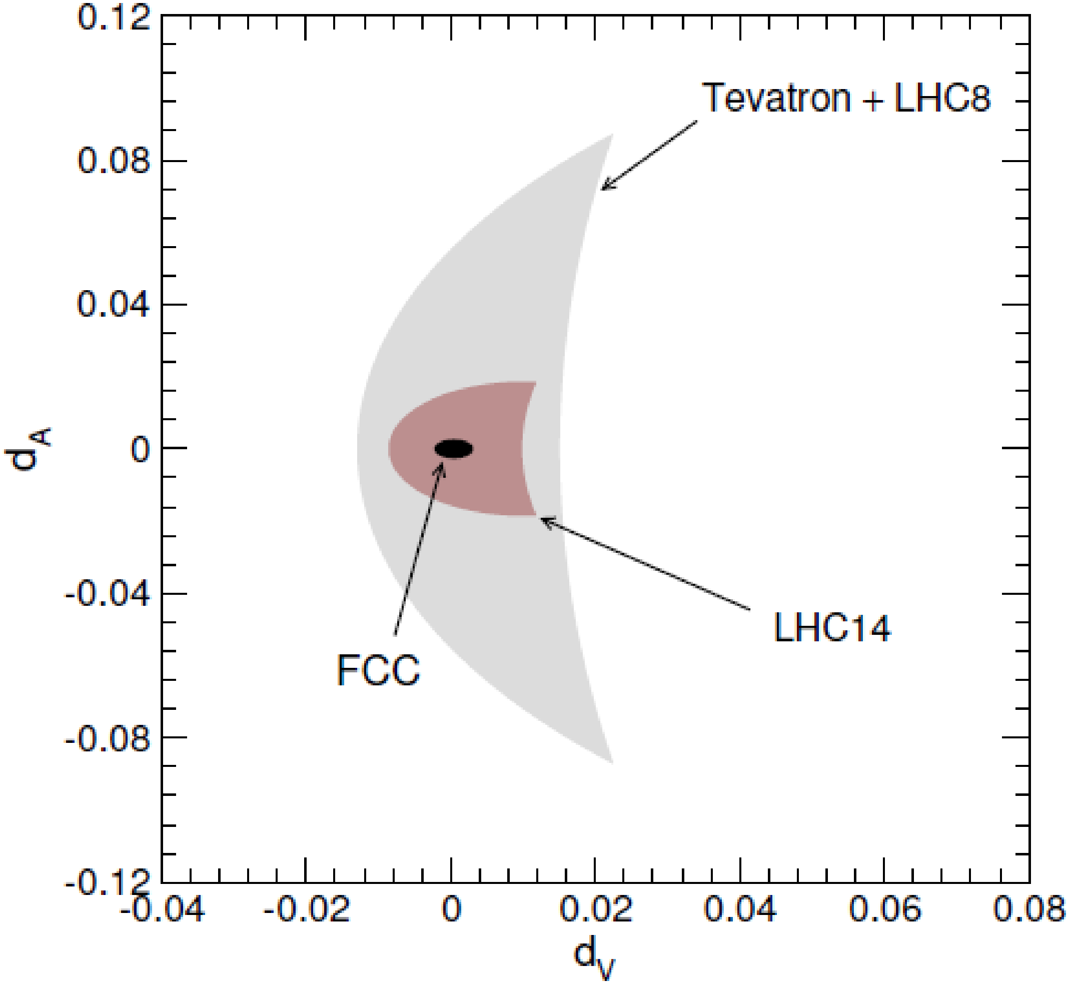
Top and QCD

Aguilar-Saavedra et al., arXiv:1412.6654

Top quark chromomagnetic and chromoelectric dipole moments

$$d_V = \frac{\sqrt{2}\, v\, m_t}{g_s \Lambda^2} \Re\, C^{33}_{uG\varphi} \qquad d_A = \frac{\sqrt{2}\, v\, m_t}{g_s \Lambda^2} \Im\, C^{33}_{uG\varphi}$$

Ultra-boosted: $m(t\bar{t}) > 10$ TeV
Top decay to bμν
Assume 5% systematic



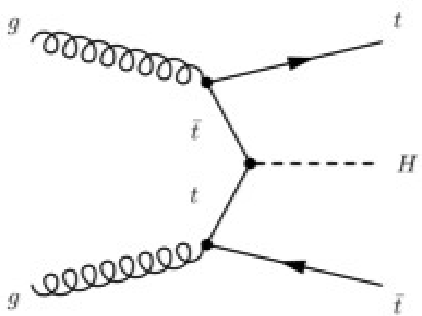
Order of magnitude improvement

Further studies would also be desirable to evaluate the complementarity of the measurements discussed in this paper, with those possible with e^+e^- collisions

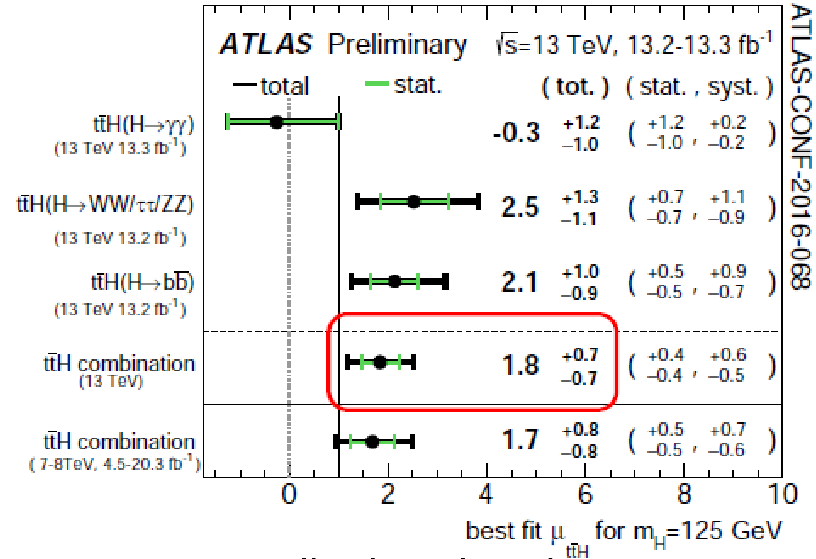
Top and Higgs

Top quark Yukawa coupling

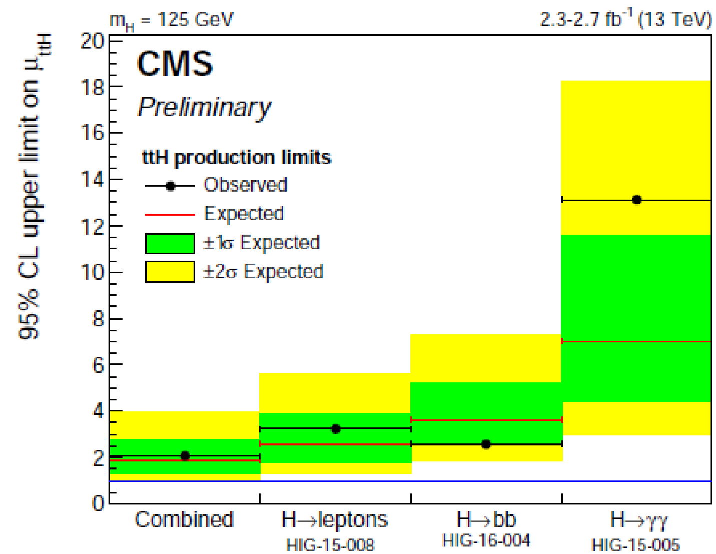
The golden couple of the SM
ttH searches in all main Higgs decay modes at 7 and 8 TeV
First 13 TeV results at this workshop



Prospects for full LHC programme:
K_u → 14-15% (300/fb)
K_u → 7-10% (3000/fb)
Snowmass Higgs report

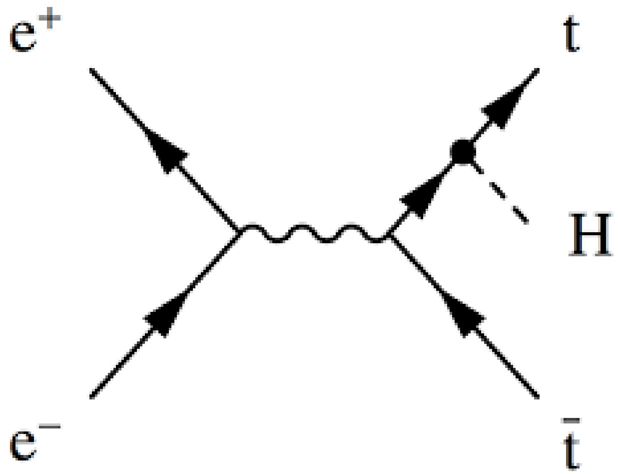


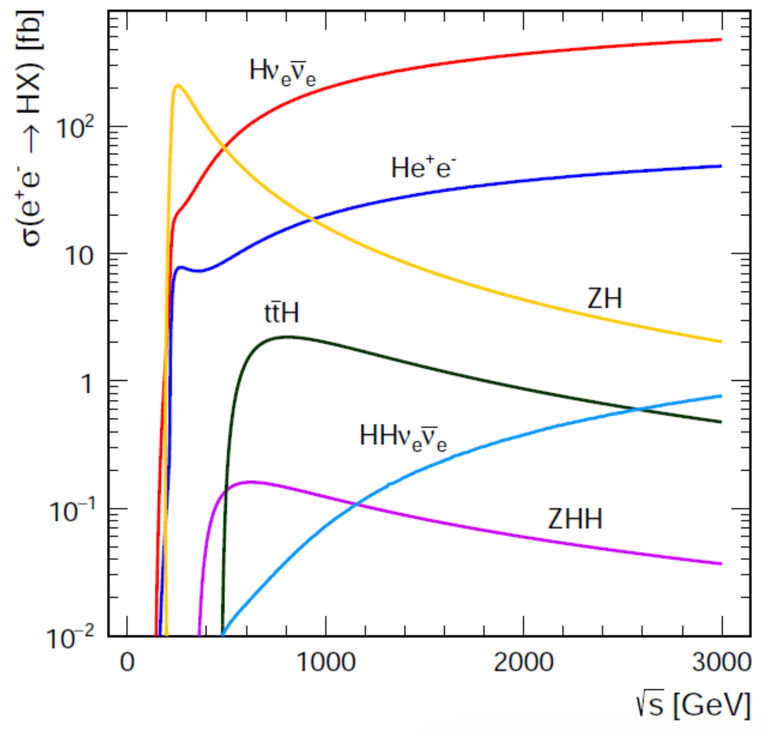
Contributions by Cinca, Schroeder, Müller on Wednesday



Audience: how do you control those bkg. shapes?

Top quark Yukawa coupling at lepton colliders





1608.07538

Bound-state effects strongly enhance cross section at threshold

→ rate at 550 GeV is three times larger than at 500 GeV

→ broad maximum around 800GeV

Top quark Yukawa coupling at lepton colliders

ILC: 3% precision achievable with 4 ab^{-1} at 550 GeV

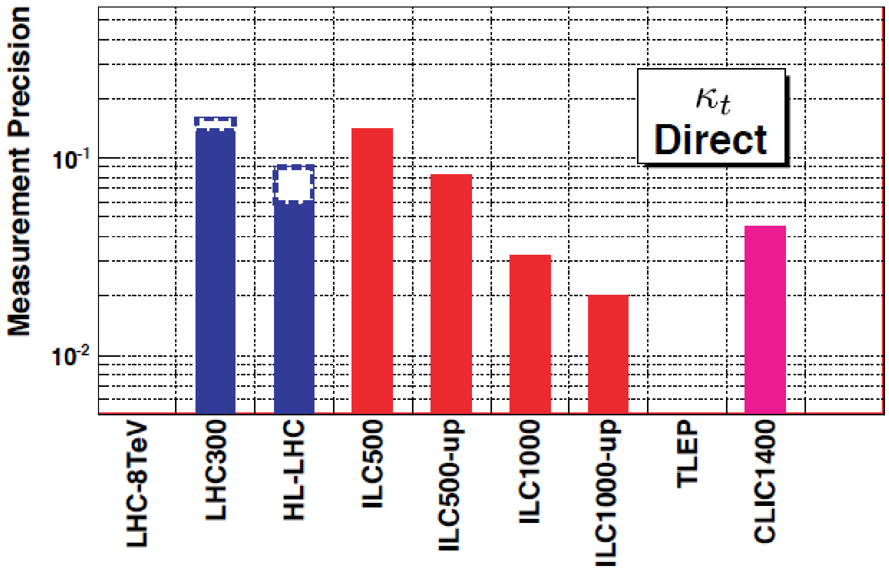
ArXiv:1506.05992

ILC: 4% precision achievable with 1 ab^{-1} at 1 TeV

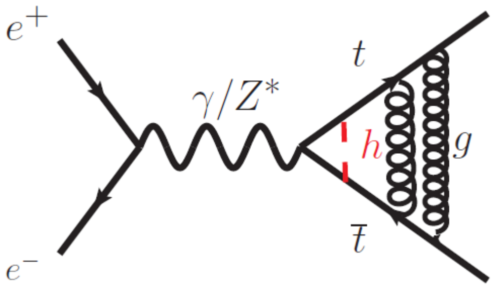
ArXiv:1409.7157

CLIC: 4% precision achievable with 1.5 ab^{-1} at 1.4 TeV

ArXiv:1608.07538



Note: 4% stat. precision achievable from threshold scan (but: large theory uncertainty)



Horiguchi et al., arXiv:1310.0563

Top quark Yukawa coupling at hadron colliders

The ttH cross section at 100 TeV is 60 times larger than at the LHC

Can we work around the theory uncertainty?
Move towards relative cross sections or ratios of processes ttH/ttZ

	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

Ratio turns O(10%) uncertainty into an O(1%) uncertainty
Even differential: cuts on p_T (Z/H, top, tt) lead to small increase only

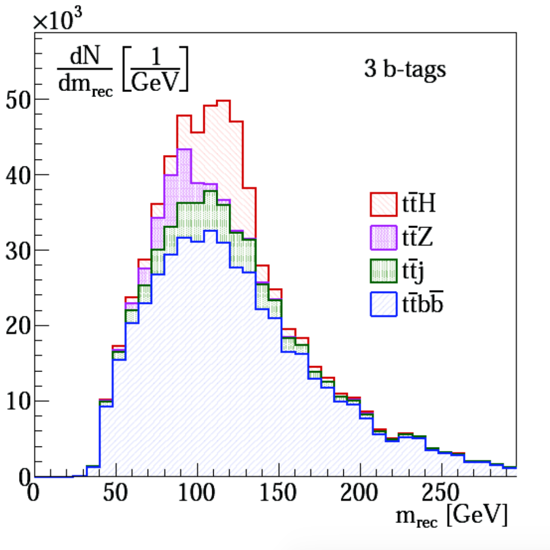
Is this the key to precision physics in pp?
it is important to verify the cancellation and establish robust uncertainties
- theory: NNLO calculation for both processes
- experiment:

CMS: R(ttbb/ttjj), R(ttγ/tt) in CMS-PAS-TOP-13-010/11 to ~25%
ATLAS: R(tt/Z) in ATLAS-CONF-2015-049 to 9%
Ratio of 7 and 8 TeV cross sections:
ATLAS: R = 1.326 ± 0.024 (stat.) ± 0.015 (syst.) ± 0.049 (lumi.) ± 0.001 (E)
Theory: R = 1.430 ± 0.013 (scale + PDF + α_s < 1%)

Top quark Yukawa coupling

High rate allows to focus on events where H → bb and hadronic top decay are sufficiently boosted to reconstruct them as “fat” jets

Fast simulation analysis achieves S/B~1/3.
Good mass resolution for H and Z candidates
Side-bands to control background normalization.



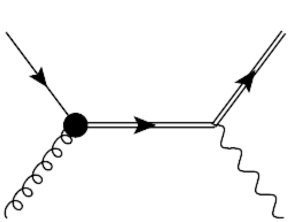
FCChh: achieve 1% precision on the top Yukawa coupling (20/ab, 100 TeV)
Mangano, Plehn, Reimitz, Schell, Shao, 2015

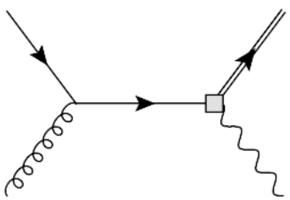
For future study: go beyond 1-parameter potential

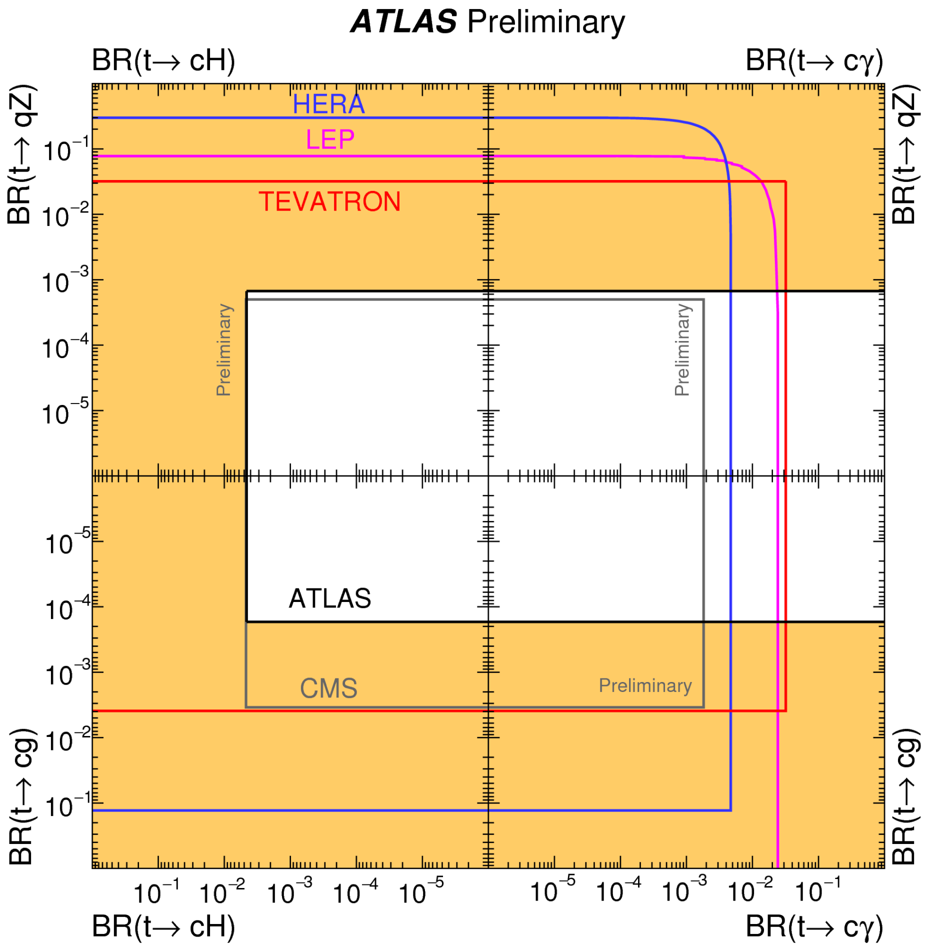
Top and FCNC

FCNC interactions

$pp \rightarrow t$ (CDF/ATLAS)
$pp \rightarrow tj$ (D0/CMS)
$pp \rightarrow t\gamma/ll$ (CMS)
$e^+e^- \rightarrow tj$ (LEP2)
$ep \rightarrow et$ (HERA)
$t \rightarrow j\gamma/ll$ (CDF/D0/ATLAS/CMS)
$t \rightarrow jh$ (ATLAS/CMS)

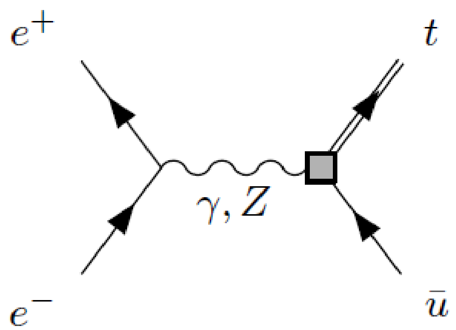




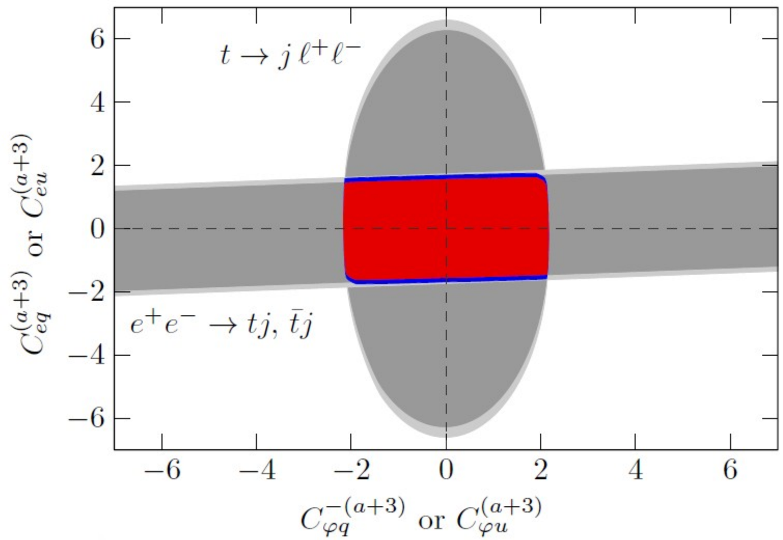


FCNC at lepton colliders

Lepton colliders may provide complementary constraints:



$e^+e^- \rightarrow tj$ limits from LEP2 in
arXiv:1412.7166
See: Gauthier Durieux' talk



Expected limits on BR(t → ch) × BR(h → $b\bar{b}$) ~ 10^{-5}

In full LC programme, Zarnecki et al., preliminary parton-level study
Order of magnitude improvement wrt Snowmass expectation for LHC + lumi upgrade

FCNC at hadron colliders

Searches for rare decays are an obvious strong point for a machine producing millions of top quarks/year

From FCChh SM physics summary (arXiv:1607.01831)

"Performing a naive rescaling of the LHC expectations [...] and assuming a luminosity of 10 ab^{-1} for the FCC, one would expect an improvement of almost two orders of magnitude, reaching a sensitivity of Br($t \rightarrow qZ$; $t \rightarrow q\gamma$) ~ 10^{-7} However, at such a level of precision the systematic uncertainties in the background predictions will likely be dominant, and a more reliable estimation of the sensitivity requires a detailed analysis."

Top EW couplings

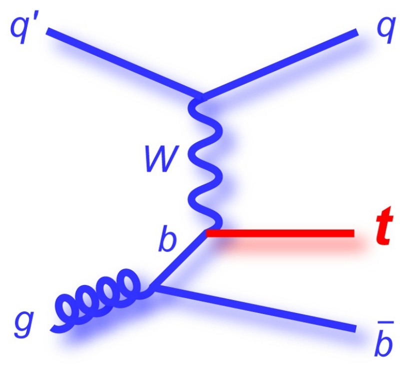
Top EW couplings

Top EW couplings relatively unconstrained
Extra-dimension models tend to predict large deviations in ttZ and ttγ

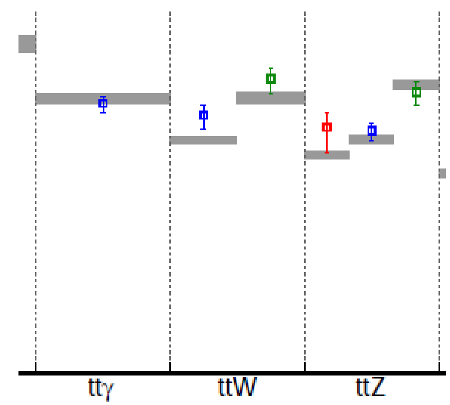
5D models by several authors, Richard, arXiv:1403.2893
4D Composite Higgs Model, Barducci, de Curtis, Moretti, Pruna, JHEP 08 (2015)

t → Wb vertex:

EW single top production:
Cross section to
Top decay
Helicity fractions and beyond

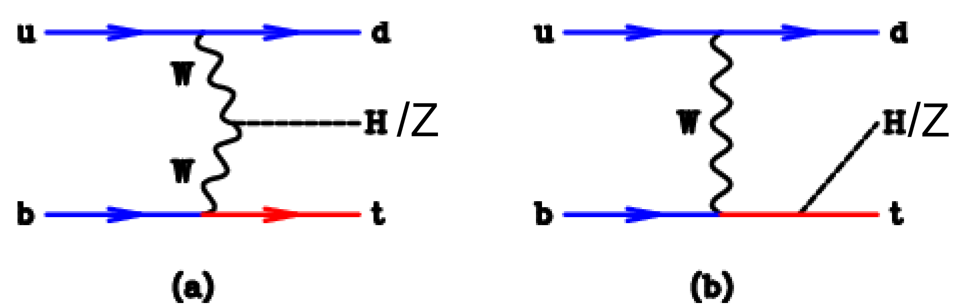


Khvastunov, this workshop.
CMS. 7, 8, 13 TeV



associated production
Access to $t\bar{t}Z$ and $t\bar{t}\gamma$ vertex
Cross section measured to 30%
10-20% theory unc. at NLO

…. single top + Z, single top + H

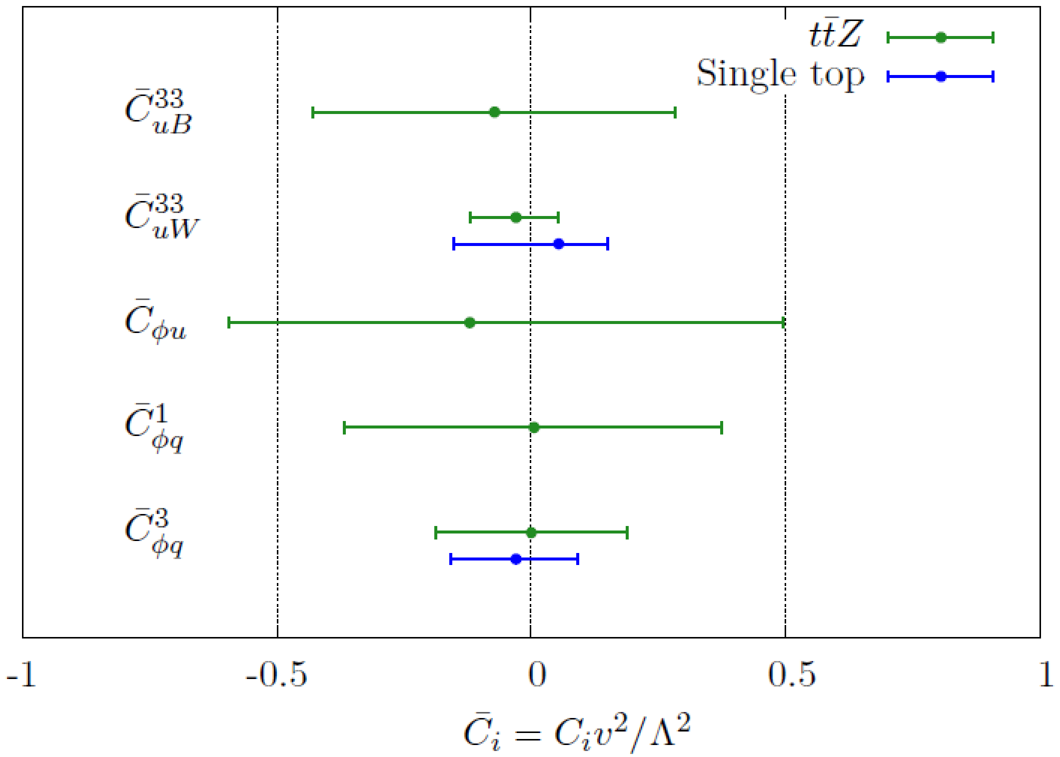


Top EW couplings: LHC status

Simultaneous fit to Tevatron and LHC data

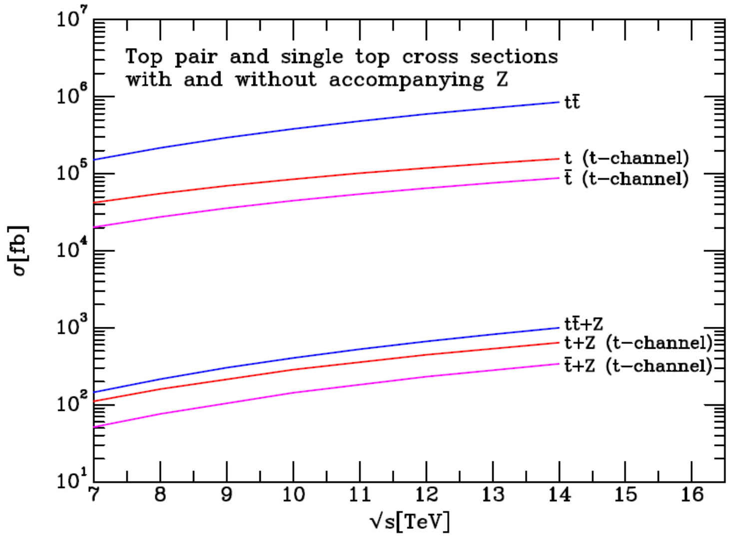
arXiv:1506.08845, arXiv:1512.03360

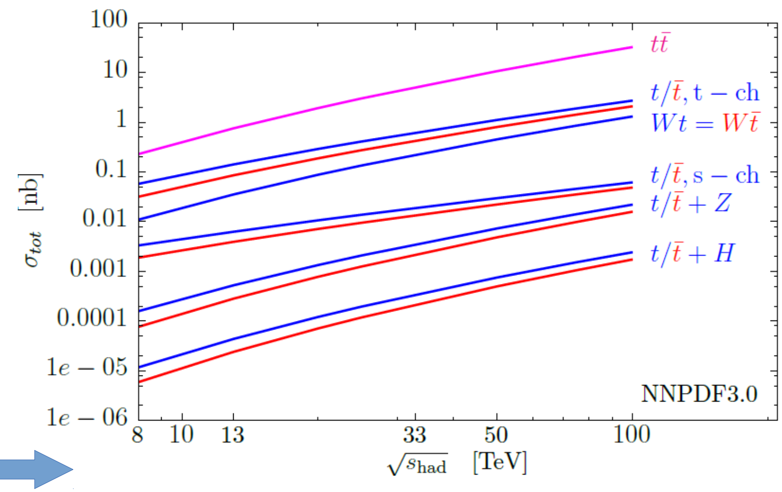
Single top production, ttZ



Associated production at 100 TeV

Analyses of still “rare” processes to profit most from increase in rate.





ArXiv:1607.01831

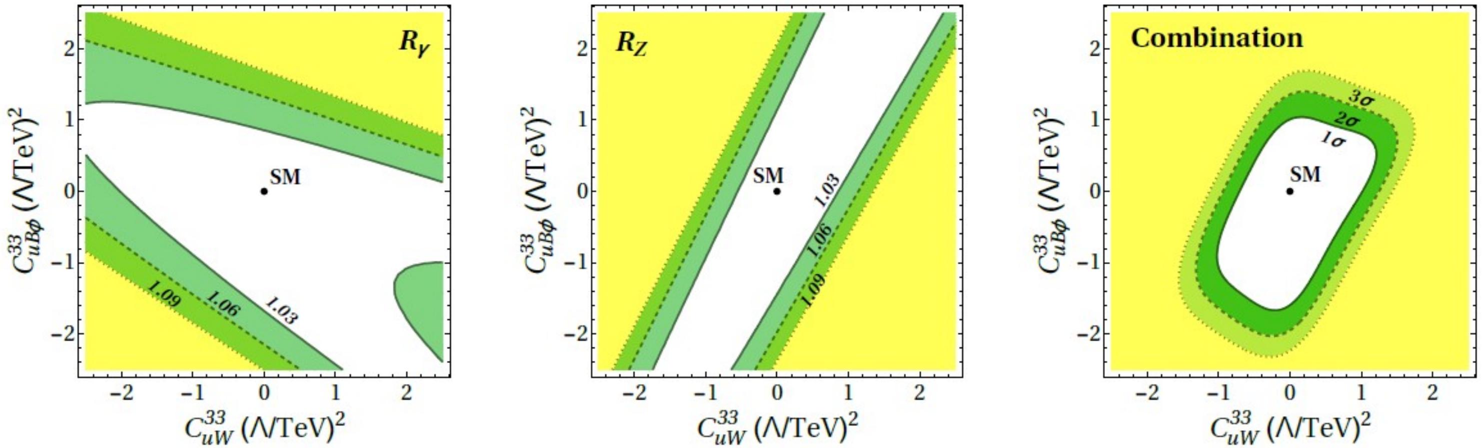
Factor 50 increase in ttZ rate; even tZ and tH become accessible

	$t\bar{t}$	$t\bar{t}t\bar{t}$	$t\bar{t}W^{\pm}$	$t\bar{t}Z^{0}$	$t\bar{t}WW$	$t\bar{t}W^{\pm}Z$	$t\bar{t}ZZ$
σ(pb)	$3.2 \cdot 10^4$	4.9	16.8	56.3	1.1	0.17	0.16

$t\bar{t}Z$ associated production

Roentsch and Schulze, arXiv:1501.05939
Schulze and Soreq, arXiv:1603.08911

Form cross section ratios (ttZ/tt and ttγ/tt) to cancel theory uncertainty (~20%)
Resulting uncertainty from scale variations = 3% in Schulze & Soreq, 2016



Differential distributions to boost sensitivity: *pT(Z)*
Baur, Juste, Orr, Rainwater, 2004, Rontsch, Schulze, 2014/2015

C_{2V} = weak magnetic dipole moment = $\sqrt{(2)}[\frac{v^2}{\Lambda^2}]\Re(c_W C^{33}_{uW} - s_W C^{33}_{uB\varphi})$

C_{2A} = (CP violating) weak electric dipole moment = $\sqrt{(2)}[\frac{v^2}{\Lambda^2}]\Im(c_W C^{33}_{uW} - s_W C^{33}_{uB\varphi})$

FCChh has the potential to boost the constraints EW dipole moments

arXiv:1607.01831

	$C_{1,V}$	$C_{1,A}$	$C_{2,V}$	$C_{2,A}$
SM value	0.24	−0.60	< 0.001	≪ 0.001
13 TeV, 3 ab^{-1}	[−0.4, +0.5]	[−0.5, −0.7]	[−0.08, +0.08]	[−0.08, +0.08]
100 TeV, 10 ab^{-1}	[+0.2, +0.28]	[−0.63, −0.57]	[−0.02, +0.02]	[−0.02, +0.02]

Top EW couplings at lepton colliders

$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(\underline{F_{1V}^X}(k^2)+\gamma_5\underline{F_{1A}^X}(k^2)\right)-\frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(i\underline{F_{2V}^X}(k^2)+\gamma_5F_{2A}^X(k^2)\right)\right\}$$

Prospects for 500 GeV ILC

ArXiv:1307.8102, arXiv:1505.0620

Measure 2 observables for 2 beam polarizations at ILC500 or CLIC380:

$$\begin{matrix}\sigma(+) & A_{FB}(+) \\ \sigma(-) & A_{FB}(-)\end{matrix} \qquad \left.\begin{matrix}(+=e_R^-) \\ (-=e_L^-)\end{matrix}\right\} \Rightarrow \left\{\begin{matrix}F_{1V}^\gamma & * & F_{2V}^\gamma \\ F_{1V}^Z & F_{1A}^Z & F_{2V}^Z\end{matrix}\right\}$$

Measure **Extract**

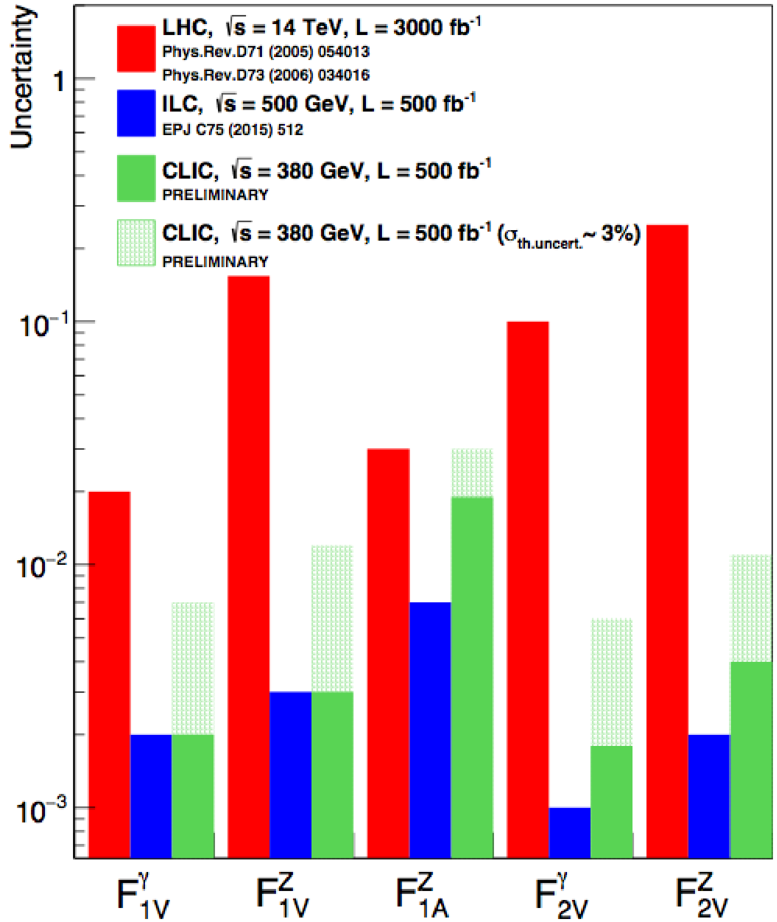
380 GeV collider has similar sensitivity

Caveat: theory unc. Exception: Z-F_{1A}

FCC-ee, Janot et al., arXiv:1503.01325, 1509.09056

ILC ME method, arXiv:1503.04247

Study of CP violating form factors coming soon!

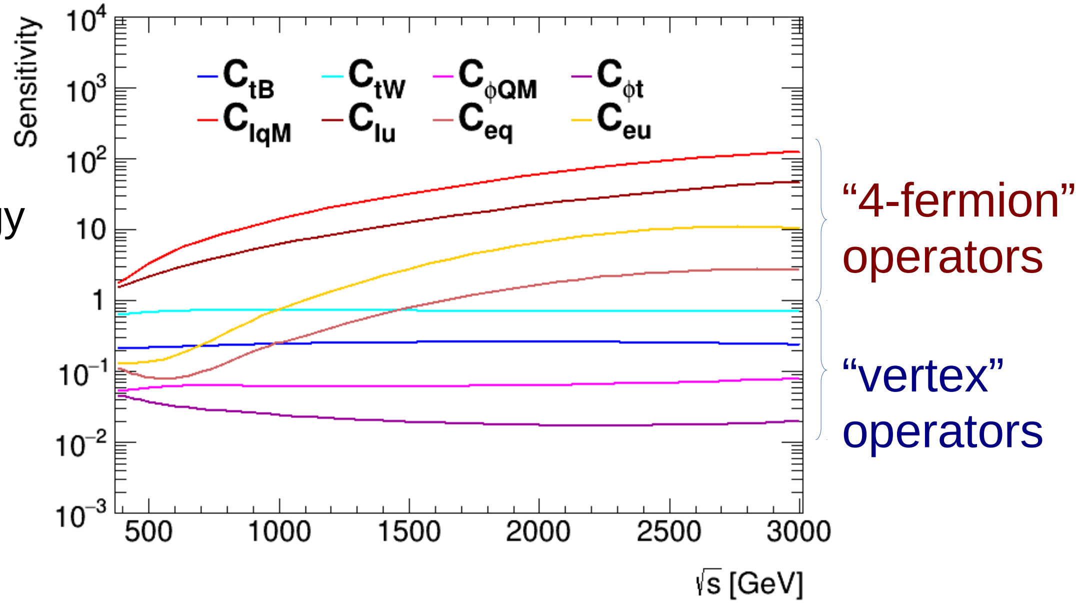


Towards a complete comparison

Adopting EFT framework

Including four-fermion operators
→ much better constrained at high energy

Durieux, Perello, Zhang, Vos, preliminary



Comparison to current LHC result based on all data (i.e. TopFitter)

Keen to add updated LHC (HighLumi) prospects

Bringing in FCChh prospects (Schulze et al., Aparisi)

Understand potential of sub-threshold e^+e^- collider operation

The future of top physics: highlights

Top physics at future facilities has the potential to deliver the transformative discovery that this field needs

LHC + HighLumi programme: covered by Patrizia

Lepton collider prospects:

= 350 GeV: top mass measurement to 50 MeV precision
> 350 GeV: Unrivalled sensitivity to ttZ and ttγ vertices
>> 500 GeV: direct top Yukawa coupling to 4%
Challenges: control of systematics to per mil level

100 TeV hadron collider targets:

Greatly enchaned mass reach for searches
Constraint of ttg vertex improves by an order of magnitude
(and qqtt 4-fermion operators)
Top Yukawa coupling to 1%
Challenges: control of systematics to % level, ultra-boosted production

Wanted: a one-plot summary of the top physics potential of the next decades (taking advantage of progress on EFT fits)